

Environmental evaluation of dish-Stirling technology for power generation

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Abstract

Dish-Stirling technology for power generation (Stirling engine driven by renewable energy, such as solar) is a promising development in electricity generation. The efficiency value, approximately 30% of normal direct solar radiation converted to electricity (Romero, 2010), is the highest among other solar energy generation systems. In the comparison against other solar energy exploitation alternatives, the environmental evaluation of the dish-Stirling technology must be taken into account. The aim of this paper is to provide a comparative environmental assessment of a dish-Stirling technology with respect to a similar photovoltaic facility. The Life Cycle Assessment procedure has been applied, and the results have been analysed in terms of CO₂-equivalent emissions as well as using two impact evaluation methods: Eco-indicator 99 and CML2. The results show that the level of environmental impacts is similar for both technologies. © 2012 Elsevier Ltd. All rights reserved.

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1. Introduction

Renewable energy plays an important role regarding future long-term sustainability for energy production and consumption. Nowadays, an increasing development of the technologies associated to exploitation of renewable energy sources is occurring due to the depletion of conventional fossil fuel energy sources along with environmental degradation caused by its consumption. In particular, electricity generation is responsible for the greatest amount of fossil fuel consumption and consequent generation of emissions. If this fact is considered together with the rising

trend for electricity consumption in the coming years (IEO, 2008), the environmental risk evaluation connected to energy production will be a major concern for policy-making. Thus, environmental evaluation is one of the key tools for policymaking, where such evaluation is used to promote environmentally-friendly energy sources.

When selecting and planning the energy technologies to be implemented and promoted, not only local inputs should be considered, but also global environmental loads with a broad perspective. In this respect, environmental evaluation must take into account all the life phases for energy production and consumption and, particularly in the systems for renewable sources exploitation, the design of the facility itself is a major concern. The environmental evaluation for electricity production is favorable for renewable energies when compared to conventional sources (fossil and nuclear), when the emissions of greenhouse gas emissions per kWh of produced energy are analysed (Varun et al., 2009).

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Nuclear energy also presents adequate values of CO₂ emissions per kWh, although other issues must additionally be taken into account, such as security and treatment of residues. Generally speaking, the emissions associated with conventional energy sources occur mainly in the production phase, while systems based on renewable energies do not cause impact during operation. In the latter, the most significant environmental impact is associated with construction, transportation and dismantling of power stations and equipments. For renewable energies, the environmental impact expressed in CO₂ emissions per kWh, in increasing order, is: wind energy, hydraulic and solar thermal, followed by biomass and, finally, solar photovoltaic (Varun et al., 2009). Thus, it is assessed that solar thermal energy should be prioritized in relation to solar photovoltaic for locations where sun energy has a high potential for use in electricity generation.

The dish-Stirling technology is one of the high concentration solar thermal technologies, together with central receiver and parabolic trough technologies. The three technologies use the concentrated power of the sun to produce energy by means of different power cycles. In the case of dish-Stirling, a dish receiver is used to collect and direct the sun rays in such a way that the concentrated sun energy is transferred to the fluid inside a Stirling engine. This engine is responsible for producing the power that will be converted to electricity.

In spite of the fact that the dish-Stirling technology is still not a long-term proven and mature technology (Bravo, 2010), the high potential for its use originates from (Romero, 2010): (i) high efficiency (approximately 30%) of normal direct isolation into electric power; and (ii) modularity, consisting on units varying from 7 to 25 kW. Thus, dish-Stirling could play an important role for future systems of distributed energy where it could be competitive with current commercial systems, such as photovoltaic and diesel generation (Pérez et al., 2008). The use of dish-Stirling technology in large scale applications is also in the future plans of industrial companies involved in its development, where the objective is to decrease the cost of energy production to approximately 0.08 €/kWh (SBP, 2010). This value is in line with the value of 0.06 €/kWh fixed by the U.S Department of Energy (DOE) for 2011 (EIA, 2012).

Environmental evaluation presents relevant information particularly when comparing the dish-Stirling technology with other renewable energy-based technologies potentially used in the same conditions, such as photovoltaic energy. Although there is existing information on this comparison (Varun et al., 2009), the study has not been carried out considering the same perspectives and considerations (such as location and size of the facilities compared). In addition, the environmental evaluation was presented with a focus on CO₂ emissions. Obviously this is a major environmental criterium due to its contribution to global warming, which is one of the main environmental issues and threats for humankind. However, a complete environmental

evaluation must take into account further aspects, so herein the methods Eco-indicator 99 and CML2 for impact evaluation have been considered, with respectively eleven and ten impact categories, covering a variety of environmental aspects much wider than only CO₂ emissions.

The objective of this study is to evaluate the environmental impact of a 10 kW dish-Stirling facility used for distributed energy, and compare it against a similar photovoltaic facility by using a broad variety of environmental aspects. The same procedure and database for system characterization is used for both technologies, so the results are useful to establish a reliable comparison by using the same environmental damage indicators. The main restriction for the analysis carried out is the system description, since data availability for the dish-Stirling system is limited due to confidentiality reasons.

To this end, the Life Cycle Assessment (LCA) procedure was utilized to analyse the entire range of environmental damages associated with products and services. In general, LCA covers the process of production and use, providing a comprehensive view of the environmental impact. LCA is used to determine the input flows of materials and energy through the definition of components and technical processes, starting from raw material extraction, intermediate and final manufacturing processes, packaging, transport, use, and finalizing with disposal. The LCA procedure has been standardized by the International Organization for Standardization (ISO) in the ISO 14040 series (ISO 14040; ISO 14044). LCA consists of four phases: goal and scope definition, Life Cycle Inventory (LCI) analysis, Life Cycle Impact Assessment (LCIA) and interpretation of results. The inventory analysis consists of collecting information regarding inputs and outputs of material and processes. A result of the inventory is the evaluation of CO₂ emissions, which also has been used to compare the technologies. The impact on an entire variety of environmental aspects is obtained through a specific impact evaluation method. Herein the Eco-indicator 99 and CML2 methods have been used. In the interpretation, the most important contributions are studied, together with sensitivity analysis to qualify the results and conclusions.

This paper is organized in two main sections: literature review and the comparative Life Cycle Assessment (LCA) of dish-Stirling vs. photovoltaic facility. The first section is useful to analyse methods for environmental evaluation and results obtained so far, and the current study intends to overcome some limitations previously stated. The first section also establishes a comparison of the current state-of-the-art of environmental evaluation for renewable energy technologies. The second section describes the LCA procedure, including data on system modeling and finally focusing on the results obtained and interpretation.

2. Literature review

The aim of this literature review was to establish the current status of analysis performed for dish-Stirling and

photovoltaic systems. The main objective was to collect information on these technologies concerning the description of the system, and tools and results already mentioned in existing studies. Most of the information gathered was related to photovoltaic energy, mainly for silicon technology, which is the most used nowadays. There are also studies including new technologies for photovoltaic systems, such as thin film or alternative materials to silicon.

The available information related to dish-Stirling systems is limited (only one study has been identified), probably due to the current status of this technology, closer to demonstration than to serial production.

The most general work related to the environmental evaluation of energy sources is a review of the whole range of power generation technologies, presenting the carbon dioxide-equivalent ($\text{CO}_2\text{-eq}$) emissions per kWh produced (Varun et al., 2009), including solar thermal and photovoltaic technologies. $\text{CO}_2\text{-eq}$ is a measure used to compare the emissions from various greenhouse gases based upon their global warming potential. This article gathers information on different technologies in studies carried out by different researchers. Thus, there is a limited reliability in the comparison of values, since these studies were not carried out with the same procedures and do not make the same considerations. However, an interesting starting point for any further analysis is to define a magnitude for all power generation technologies, which enables the establishment of a relative order between conventional fossil fuels and renewable energies. One first result is that, for renewable energies, there is a very low contribution of the operation phase and the emissions are produced mainly during the phases of equipment construction and installation. This is opposite of what happens with conventional fossil fuels, in which the emissions and environmental loads generated during the construction and installation phases is one order of magnitude lower than the environmental burden associated with operation.

Table 1 shows the environmental emissions for the systems considered in Varun et al. (2009). The general trend shows favorable values for renewable energies, although the ranges are quite wide for some technologies. In the case of wind energy, for example, the minimum values correspond to small installations without specific information on the utilization factor. As for photovoltaics, emissions depend on the technology used and degree of development of this technology, and also on the location, since it has a strong relationship with irradiation values and therefore with system efficiency. From the values of this review, it can be observed that the constant evolution of photovoltaics is leading to lower environmental impacts. In particular, the minimum value presented for this technology (53.4 g- $\text{CO}_2\text{-eq/kWh}$) is for the amorphous silicon technology in a study performed in Japan (Hondo, 2005).

Dish-Stirling technology is included in the solar thermal systems, and a detailed attachment is presented in Table 1. The minimum value for solar thermal technologies corresponds to a 1 MW dish-Stirling technology facility

Table 1

Comparison of power generation technologies, conventional and renewable systems (unit: g- $\text{CO}_2\text{-eq/kWh}$) (Varun et al., 2009).

		g $\text{CO}_2\text{-eq/kWh}$
<i>Conventional systems</i>		
Coal fired		975.3
Oil fired		742.1
Gas fired		607.6
Nuclear		24.2
<i>Renewable systems</i>		
Wind		9.7–123.7
Hydro		3.7–237
Biomass		35–178
Solar PV		53.4–250
Solar thermal		13.6–202
<i>Systems:</i>	<i>Paraboloidal dish</i>	13.6
	<i>Central receiver</i>	43
	<i>Parabolic trough</i>	196
	<i>Central tower</i>	202

(13.6 g- $\text{CO}_2\text{-eq/kWh}$). Varun et al. (2009) foresee the potential of dish-Stirling technology to minimize environmental impacts in relation to photovoltaics. As previously mentioned, this review is useful for an initial analysis, but the values correspond to different facility characteristics and sizes, which can be determinant in the environmental evaluation result.

A more detailed literature analysis has been carried out for photovoltaic energy; there are studies where specific information is presented regarding different technologies. However, after systematic reviews, only the study of Varun et al. (2009) was found for dish-Stirling technology.

The existing studies on photovoltaic systems were useful to understand softwares, databases, impact evaluation methods, and types of facilities analysed. Mohr et al. (2009) compared multicrystalline silicon and thin film technologies (GaInP/GaAs – gallium indium phosphide/gallium arsenide). The tools used for this study were SimaPro 7.1.8 software, Ecoinvent 2.01 database, and the CML 2001 impact evaluation method. The functional unit considered a facility of 1 kWp with an irradiation of 1000 kWh/m² in Western Europe and a lifetime of 30 years. The phases included in the analyses were production, maintenance and disposal. The results obtained for GaInP and GaAs technologies were quite similar. The use of electricity from PV modules was also considered for the life cycle (instead of using conventional electricity). This translates into a favorable impact regarding the following impact categories: global warming, abiotic depletion, acidification and photochemical oxidation. However, reductions in toxicity are negligible.

Alsema et al. (2006) also compare silicon and thin film technology (CdTe – cadmium telluride) in both present and future expectations. The environmental impact results were obtained through a full Life Cycle Assessment, using software SimaPro 7 and Ecoinvent 1.2 database. The greenhouse gas emissions were evaluated by the IPCC 2001 GWP 100a method (v. 1.02). The photovoltaic sys-

tems were located in central and south Europe (irradiation values varying from 1000 to 1700 kWh/m²/year), with a lifetime of 30 years and a system performance ratio of 0.75. The results were presented in the form of greenhouse gas emissions (g-CO₂-eq/kWh) and energy pay-back time (EPBT), and a comparison was also included for conventional power generation systems. For photovoltaics, greenhouse gas emissions were in the range of 25–32 g-CO₂-eq/kWh (25 for thin film technology and 32 for crystalline silicon), which could decrease to 15 g-CO₂-eq/kWh in the future for both technologies. Conventional power generation values vary in the range of 120–400 g-CO₂-eq/kWh (Alsema et al., 2006).

The emissions associated with photovoltaic systems are mainly due to construction processes. Therefore PV energy systems have a high potential to be a low-carbon energy supply technology, although further efforts should be made to reduce the energy required for silicon processes (production of solar modules). The development of thin film technologies represents the major potential of photovoltaic systems for the future. Energy pay back time for crystalline silicon PV systems is 1.5–2 years for South-European locations and 2.7–3.5 years for Middle-European locations (Mohr et al., 2009). For silicon technology, clear prospects of a reduction of energy input exist, and an energy pay-back of 1 year may be possible within a few years.

Thin film technologies have energy pay back times in the range of 1–1.5 years (South Europe) (Alsema et al., 2006). Fthenakis and Kim (2011) presented the most updated review of information regarding environmental impact for photovoltaic energy, with a comprehensive overview of system description and existing studies. The results are mainly expressed in terms of EPBT and CO₂-equivalent emissions, and show comparisons for the different photovoltaic technologies, both in present and future expectations. The results have the following common considerations: Southern European irradiation of 1700 kWh/m²/year, performance ratio of 0.75 and a lifetime of 30 years, with the exception of thin film technology (CdTe), which considers US isolation of 1800 kWh/m²/year and a performance ratio of 0.8. Results show that EPBT and CO₂ emissions are favorable for thin film technology: EPBT of 0.7 years and 18 g-CO₂-eq/kWh, compared to an EPBT of approximately 2.4 years and 37 g-CO₂-eq/kWh for monocrystalline silicon (the most used nowadays).

Multicrystalline and ribbon silicon present medium values in relation to thin film and monocrystalline silicon technologies (Fthenakis and Kim, 2011). However, future evolution of photovoltaic technologies could show that the values of EPBT and CO₂ emissions decrease significantly and that silicon and thin film will present similar values: EPBT of 0.5 years and 10 g-CO₂-eq/kWh (Fthenakis and Kim, 2011). PV industry is achieving cost savings and advanced performance simultaneously, which translates into a decrease of environmental impacts. In fact, conversion efficiency, material usage, and production energy

efficiency of both Si and CdTe PVs are improving rapidly (Fthenakis and Kim, 2011). The environmental evaluation of these systems should be therefore frequently updated in order to follow such evolution.

Other studies focused on analysing the PV technology phases with higher impact, such as the work of Stopatto (2008), where the multicrystalline silicon technology is analysed. The LCA software used in this case was Boustead Model V5.0, where the environmental impact for the construction of a photovoltaic panel of surface 0.65 m² was analyzed, with detailed information on the construction phases. The impact associated with transport, installation and operation were not taken into account. The lifetime considered was 28 years, and the environmental impact was calculated for the following factors: energy necessary for construction (1494 MJ/panel), greenhouse effect or global warming potential (80 kg-CO₂-eq per panel) and energy pay-back time (6.5 years). Sensitivity analysis can be performed to analyse construction and operation alternatives for photovoltaic energy, as in the work of Kannan et al. (2006). The functional unit of this analysis was a 2.7 kWp monocrystalline silicon system located in Singapore. The results were given in terms of energy required, EPBT and CO₂ emissions. The analysed scenarios were: 50% reduction in the energy required for construction, replacement of metallic support by concrete, and increase of efficiency. The most significant reductions are for the first alternative, a 50% reduction in energy use for manufacturing a solar PV, resulting in reductions of energy (2.91–1.72 MJ/kWh_e), EPBT (5.87–3.48 years) and CO₂ emissions (217–129 g/-CO₂-eq kWh_e). Obviously the implementation of the three alternatives will further reduce the three results analysed.

Only one study presented specific analysis of dish-Stirling technology (Cavallaro and Ciraolo, 2006): a 1 MW facility for mass power production located in Italy, consisting of 17 solar dishes generating steam to drive five Stirling engines to produce energy, with a solar-to-electrical conversion efficiency of 18%. This facility is different from the one analysed herein, where each dish is coupled to a Stirling engine forming an isolated unit with conversion energy efficiency of approximately 30%. The tools used in Cavallaro and Ciraolo (2006) for dish-Stirling evaluation were SimaPro software, ETH-ESU 1996, IDEMAT 2001 and BUWAL 1996 databases, and Eco-indicator 99 (EI-99) impact evaluation method. The analysis was made considering the facility construction, with and without recycling. The phases included were: construction of the plant, manufacture of the large dish solar collectors and Stirling engines, extraction and supply of consumables, transport, and decommissioning and recycling of the power plant. The environmental effects were valued in terms of CO₂, SO₂ (acidification), CFC11 (ozone layer), PO₄ (eutrophication), SPM (winter smog), C₂H₄ (summer smog) and solid waste. The CO₂ values must be highlighted: 7.3 g-CO₂-eq/kWh with recycling and 13.6 g-CO₂-eq/kWh without. The dish-plant construction was the most significant

phase, and recycling presented a lower contribution but nevertheless is a relatively important value. As a general conclusion, it is remarked that the environmental impact associated with the entire life cycle is negligible in relation to traditional fossil fuels power stations. The results obtained were rather encouraging and deserve to be studied further, to develop a comparative study with other thermodynamic solar technologies that use solar concentrators.

3. Description of the analysed facilities

As previously mentioned, the dish-Stirling system is one of the solar thermal technologies for power generation and in this system, the sun rays supply the energy that drives the Stirling engine. A parabolically curved concentrator reflects the parallel solar rays and sends them to one focal point. The dish moves throughout the day to follow the sun's trajectory, so the tracking system is one of the key elements in this technology. A heat exchanger located at the focal point absorbs the radiation, heating the thermal transfer fluid of the Stirling engine. The engine transforms heat into rotational energy and then into electrical power through a generator attached directly to the crankshaft of the motor. The essential components of a dish-Stirling system are the concentrator, the Stirling engine with a solar receiver and the solar tracking device.

The concentrator (paraboloidal dish) is supported by a metallic structure fixed on the ground with concrete, to provide the system with the necessary stability to guarantee a good focus of concentrated radiation. The dish-Stirling technology has been used in several research and development projects with a number of demonstration facilities supported by different companies and research bodies around the world (Manzini et al., 2003). The systems vary from 3 to 50 kW per unit. Herein a 10 kW system of the Schlaich Bergermann und Partner (SBP) company was selected, due to availability of information for the Life Cycle Assessment procedure.

An SBP system is depicted in Fig. 1. The main characteristics of the different components of this system are described next (Bravo, 2010): the concentrator, also called dish receiver, consists of twelve independent segments of glass fiber. The segments are assembled in a paraboloidal shape, externally tensioned to guarantee the proper shape. A layer of thin glass is added in order to obtain a high reflectivity (94%). The maintenance of the dish-Stirling facility includes cleaning the concentrator to guarantee maximum efficiency.

The Stirling engine together with the alternator is the unit that converts the concentrated solar energy into electricity. The engine efficiency is of approximately 30%. The SBP facility uses hydrogen as a working fluid for the Stirling engine. The engine used for this facility is a SOLO-161 from the German company Solo Kleinmotoren GmbH. A current concern for this facility is the leakage level, which makes it necessary to periodically replace the



Fig. 1. SBP system (web SBP. <www.sbp.de>).

working fluid. However, large scale applications are designed to minimize these leaks.

The solar receiver is the heat exchanger, mounted on the Stirling engine to transfer energy from the sun to the working fluid of the engine. A ceramic cavity receives the sun rays reflected from the concentrator. The heat exchanger can be direct illuminated tubes or the reflux type using a liquid metal as an intermediate fluid for heat transfer (heat pipe). The SBP facility uses direct-illuminated tubes, where the sun radiation impinges on a tube bundle, and the working fluid of the Stirling engine flows inside. The heat exchanger consists of 78 tubes of Inconel 625 with an external diameter of 3 mm, joined through a brazing process. The system is supported by a metallic structure made of steel bars with an approximate weight of 3700 kg. The concrete base is approximately 150 ton.

For the photovoltaic system, a 10 kW monocrystalline silicon technology facility was selected, with typical roof installation. The system includes the photovoltaic panels, the electric installation and the AC/DC converter. The definition of this facility corresponds to the description of a photovoltaic facility, with façade installation, single-Si, laminated, integrated, installed on a building (Ecoinvent database, version 2.07 – PRÉ Consultants, 2007).

4. Life Cycle Assessment

Through Life Cycle Assessment, the embodied energy and emissions are calculated and translated into environmental and social effects. These relevant aspects of renewable energy development are valued by the software SimaPro v. 7.3 (2010), a specialized LCA tool. The analysis consists of an inventory of products and processes involved, which are then valued in terms of emissions and energy, and a later impact evaluation translates environmental effects into valuable impact categories. The present study is mainly focused on the comparison of these impact categories. SimaPro was used to calculate the

impact associated with the production and final disposal of the dish-Stirling and photovoltaic facilities. The software includes several inventory databases with thousands of processes, plus the most important impact assessment methods. Selection of database and impact assessment method are very important *a priori* steps in a LCA, as the results will be depend on this decision.

Regarding the database, it is important to select an updated version that contains the most accurate and representative information possible for material and processes. If the inventory of the system uses the same database the results are more reliable (coherence and uniformity in the criteria for emissions and resources calculation). A preliminary analysis of the existing databases is required to guarantee a complete definition of the dish-Stirling and photovoltaic systems. The Ecoinvent database (SIMAP-RO, 2010) version 2.07 was used, since it is considered one of the most complete and updated databases commercially available for LCA. Therefore the inventory results (emissions and resources employed) use the Ecoinvent database. CO₂ equivalent emissions will be utilized in a comparison with the literature review presented in the previous section.

There are different available impact assessment methods that utilize different environmental criteria and therefore evaluate and assess different environmental aspects (Carvalho et al., 2011a). The two assessment methods that have been used in this research work, Eco Indicator-99 method and the CML2 method, are briefly justified and explained next.

4.1. The Eco-indicator 99 method (EI-99)

The Eco-indicator 99 method was selected because it is widely used in LCA, incorporating relevant environmental burdens into different impact categories, which in turn allow the evaluation of damages to human health, ecosystem quality, and resources. Furthermore, the LCA results of EI-99 are aggregated into an easily understandable number, the Single Score, and from a computational point of view, are appropriate to be integrated into an optimization model. The EI-99 method considers the values of eleven impact categories (Table 2), which are added into three damage categories (Fig. 2), weighted, and then aggregated into an index, the Single Score, which represents the overall environmental load in points. One point (pt) can be interpreted as one thousandth of the annual environmental load of one average European inhabitant. The damage models include different analysis for calculation: fate, exposure, effect, resource and damage analysis, evaluating the impact caused by emissions and resources depletion. The normalization of the values obtained for the three damage categories means obtaining isodimensional values for these categories, in such a way that it is possible to establish comparisons.

According to the ISO 14042 (2006) terminology, EI-99 is an “endpoint” method, since it calculates the damage

Table 2

Impact categories of EI-99 impact evaluation method.

Carcinogens
Respirable organics
Respirable inorganics
Climate change
Radiation
Ozone layer
Ecotoxicity
Acidification/eutrophication
Land use
Minerals
Fossil fuels

categories (human health, ecosystem quality and resources) by means of a damage model from the impact categories.

A detailed explanation of the calculations involved in the EI-99 method, according to Carvalho (2011) and Carvalho et al. (2011b), follows:

In EI-99, adverse effects on the environment are divided into three broad damage categories: Human Health, Ecosystem Quality (flora and fauna), and Resources of the Earth.

Human Health includes the idea that all human beings, in present and future, should be free from environmentally transmitted illnesses, disabilities and premature deaths. *Ecosystem Quality* includes the idea that non-human species should not suffer from disruptive changes to their populations and geographical distribution. Lastly, *Resources* includes the idea that the nature's supply of non-living goods, which are essential to human society, should also be available for future generations (Goedkoop et al., 2000).

Under the damage category of *Human Health*, EI-99 accounts for the number of people as well as the length of illnesses and life years lost due to premature death from environmental effects. This method is used by the World Health Organization and the World Bank (Sonnemann et al., 2003). Impacts on human health are well expressed by the Disability Adjusted Life Years (DALY). DALY is a health-gap measure that extends the concept of potential years of life lost due to premature death to include equivalent years of ‘healthy’ life lost by virtue of being in state of poor health or disability (Lopez et al., 2006). One DALY, therefore, is equal to 1 year of healthy life lost. Human Health accounts for effects caused by ozone layer depletion, effects caused by ionizing radiation, damage caused by climate change, respiratory effects caused by organic and inorganic substances, and carcinogenic effects on humans.

Ecosystem Quality quantifies environmental impacts on species' diversity, including vascular plants and lower organisms, considering reversible or irreversible disappearance or stress on a species in a certain region during a certain time-frame. This damage category accounts for the consequences of land use, damage caused by combined effects of acidification and eutrophication, and damage caused by ecotoxic effects. There is no uniform parameter

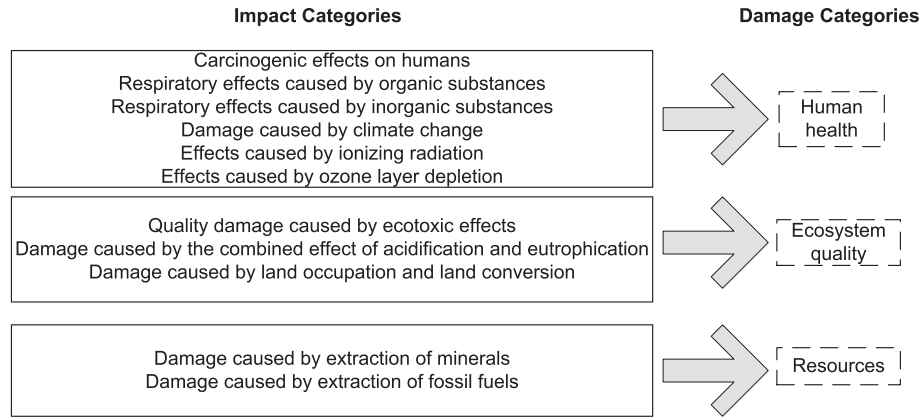


Fig. 2. Model of impact evaluation method Eco-indicator 99 (Carvalho et al., 2011a).

for this purpose, such as the DALY (Goedkoop et al., 2000). Toxicity is measured by the Potentially Affected Fraction of species (PAF, in PAF m² y), which quantifies the toxic effect on organisms (mostly lower forms) that live in water and soil (toxic stress). Damages resulting from acidification, eutrophication and land-use are measured as the percentage of species that have disappeared in a certain area due to the environmental load (Potentially Disappeared Fraction, PDF, in PDF m² y). As PAF and PDF are very different measures, the damage cannot be simply added. Considering the level at which species (assuming all species have equal importance) become affected and at which level they disappear, a conversion factor has been developed in which the PAF results are divided by 10 before they can be added to the PDF (Goedkoop et al., 2000).

With respect to the damage category of *Resources*, the models in EI-99 only consider the effects caused by extraction of minerals and fossil fuels. These effects are evaluated as the additional energy needed in the future to extract lower grade mineral and fossil resources. The additional energy is called *surplus energy* and is measured in MJ surplus. For minerals, lower grade ores are considered to require more effort to process and larger amounts of electrical or fossil fuel energy per unit of metal produced (Sonnemann et al., 2003). For fossil fuels, surplus energy is based on future use of nonconventional resources, especially oil shale and tar sands. The point in the future has been chosen as the time at which five times the cumulative extraction of the resource before 1990 has been extracted (Goedkoop et al., 2000).

EI-99 presents three different approaches to obtain the EI-99 Single Score (combining the contribution of each damage category): Egalitarian, Hierarchist, and Individualist. The Hierarchist version (H/H) was selected for the damage model herein because of its balanced time perspective, as a consensus among scientists determined inclusion of environmental effects (Goedkoop et al., 2000) and strong-held belief in preventing environmental problems through regulation (Hauschild, 2005). In the Hierarchist

version (H/H), Human Health and Resources each contribute 30%, while Ecosystem Quality contributes 40% to the final value of EI-99 Single Score (Goedkoop et al., 2000). Complete information can be found in the Methodology and Annex reports (Goedkoop and Spruiensma, 2001a, 2001b).

In order to calculate the EI-99 score, the following steps are necessary (Carvalho, 2011):

- (1) Evaluation of the inventory of resource extraction, land-use and all relevant emissions k in all processes that form the life cycle of the equipment or utility, yielding the Life Cycle Inventory LCI_k .
- (2) Calculation of the damage IM_{ic} caused in each impact category ic belonging to a specific damage category dm , provoked by each item of LCI_k . This is done by multiplying each item LCI_k obtained in step 1 by the corresponding set of damage factors $df_{ic,k}$:

$$IM_{ic} = \sum_k df_{ic,k} \cdot LCI_k \quad \forall ic$$

The damage factors are used to translate the LCI_k into the associated impacts.

- (3) *Optional*. Aggregation of each impact category into the corresponding damage category:

$$DAM_{dm} = \sum_{ic \in ic(dm)} IM_{ic} \quad \forall dm$$

where $ic(dm)$ denoted the set of impact categories ic that contributed to damage dm . This step is optional as step four can be applied directly to step two.

- (4) Determination of the Eco-indicator 99, through the application of specific normalization σ and weighting ζ factors, and final aggregation:

$$EI - 99 = \sum_{dm} \zeta \cdot \sigma \cdot DAM_{dm}$$

The normalization σ and weighting ζ factors depend on the cultural perspective, and will carry the corresponding subscript.

4.2. CML2 method

The CML2 impact assessment method was also utilized for the LCA. This method was developed by the Center for Environmental Studies of Leiden University, Holland, which is internationally recognized for its expertise and experience in this field. The CML characterization factors were largely based on work undertaken by other expert groups or researchers, e.g., the IPCC (Intergovernmental Panel on Climate Change), including new impact categories and revising and updates existing categories (BRE, 2005).

It is considered one of the main schools of methods (Joliet et al., 2003): classical impact assessment methods, which restrict quantitative modeling to relatively early stages in the cause-effect chain to limit uncertainties and group LCI results in so-called midpoint categories, according to themes. Themes are common mechanisms (e.g. climate change) or commonly accepted grouping (e.g. ecotoxicity).

The CML2 is considered to be a “midpoint” method, using only impact categories, without any further calculations. The CML2 method considers ten impact categories, shown in Table 3 (which are different from the EI-99 method), but there is no further calculation for damage categories (“midpoint” method). In this case, normalization can be applied at an impact category level, thus also enabling the comparison between different categories.

A brief overview of environmental impact categories for CML2 is presented next (Azapagic et al., 2004):

Abiotic resource depletion potential represents depletion of fossil fuels, metals and minerals. The total impact is calculated by using the abiotic depletion potential (characterization factor), expressed in kg of antimony used.

Climate change represents the total global warming potential (GWP) of different greenhouse gases (GHG), with the reference substance being CO₂. The characterization model as developed by the Intergovernmental Panel on Climate Change (IPCC) is selected for development of characterization factors. The values of GWP depend on the time horizon over which the global warming effect is

assessed. GWP factors for shorter times (20 and 50 years) provide an indication of the short-term effects of GHGs on the climate, while GWPs for longer periods (100 and 500 years) are used to predict the cumulative effects of these gases on the global climate.

Stratospheric ozone depletion potential indicates the potential of emissions of chlorofluorohydrocarbons and other halogenated hydrocarbons to deplete the ozone layer, where the reference substance is CFC-11.

Human toxicity potential is calculated by taking into account releases toxic to humans to three different media (air, water and soil). The reference substance for this impact category is 1,4-dichlorobenzene.

Photo-oxidant formation is related to the potential of volatile organic compounds and nitrogen oxides to generate photochemical or summer smog, and is usually expressed related to ethylene.

Freshwater, Marine, and Terrestrial ecotoxicity is calculated for all three environmental media and is based on the maximum tolerable concentrations of different toxic substances in the environment but different organisms. The reference substance for this compartment is also 1,4-dichlorobenzene.

Acidification potential is based on the contribution of sulfur dioxide, NO_x and ammonia to the potential acid deposition, and is expressed in kg of SO₂.

Eutrophication potential is defined as the potential of nutrients to cause overfertilization of water and soil, which can result in increased growth of biomass (algae), and is expressed relative to PO₄³⁻.

Calculation of environmental impacts using CML2 is carried out as follows:

- (1) Evaluation of the inventory of resource extraction, land-use and all relevant emissions k in all processes that form the life cycle of the equipment or utility, yielding the Life Cycle Inventory LCI_k .
- (2) Calculation of the damage IM_{ic} caused in each impact category ic for each item of LCI_k . This is done by multiplying each item of LCI_k obtained in step 1 by the corresponding set of conversion factors $cf_{ic,k}$:

$$IM_{ic} = \sum_k cf_{ic,k} \cdot LCI_k \quad \forall ic$$

The impacts are calculated relative to a conversion/characterization factor for a reference substance.

- (3) Specific normalization σ , where σ is a set of normalization alternatives (Holland 1997, Western Europe 1995, World 1990 and World 1995).

$$IM_{icN} = \sum_{dm} \sigma \cdot IM_{ic}$$

Conversion and normalization factors can be found in Guinee et al. (2002). The reference for normalization is the damage caused by a region at a given year. In SIMAP-

Table 3
Impact categories of CML2 impact evaluation method.

Abiotic resources depletion
Global warming
Stratospheric ozone depletion
Human toxicity
Freshwater aquatic ecotoxicity
Marine ecotoxicity
Terrestrial ecotoxicity
Photo-oxidant formation
Acidification
Eutrophication

RO, four normalization alternatives are presented: Holland 1997, Western Europe 1995, World 1990 and World 1995. The latter has been selected for this work because it presents a more global approach. The CML2 method does not depend on social perspectives.

Using the two aforementioned different impact assessment methods, Eco Indicator-99 (Goedkoop et al., 2000) and CML2 (Guinée, 2002) will enable the assessment of the conclusions according to different evaluation criteria. After specification of the processes, selection of databases and methods, SIMAPRO carries out all calculations of environmental impacts.

4.3. Modeling

The assumptions made on the subjects of the study are among the most important issues in LCA: this comparative analysis considered a 10 kW dish-Stirling facility for distributed generation and a 10 kW photovoltaic installation. No specific location characteristics have been considered for this comparative analysis. In order to perform a comparison of the obtained results, it is assumed that both installations are installed in the same place with the same solar radiation.

The dish-Stirling facility (SBP, 2010) was defined in SIMAPRO through its main equipment, in such a way that a complete inventory of material and processes was established. Data was collected from different documentation (Stirling Systems GmbH, 2007) and from the SBP (2010) demonstration facility in Odiello (France). No information was obtained from constructors due to confidentiality reasons. Confidentiality is also the reason why there is no data available on operation and maintenance. Thus, only construction and disposal (including assembly and transport) was considered for life cycle phases.

Such a consideration is supported by results obtained in the literature review, where it is stated that construction is the most significant phase, together with disposal (Kannan et al., 2006). Nevertheless it must be taken into account that the novelty of this technology includes an uncertainty factor in relation to reliability and maintenance of the Stirling engine (Bravo, 2010).

For the photovoltaic facility, the information was extracted from the Ecoinvent (PRé consultants, 2010) database. The technology selected was monocrystalline silicon, which is the most used currently, presenting good efficiency together with a reasonable cost. It was also assumed that the operation impact is negligible.

The lifetime for both facilities was considered to be 30 years (Cavallaro and Ciraolo, 2006), and all materials were recycled at disposal to foresee future use of the components. This is due to the fact that previous studies also included recycling (Stopatto, 2008). In any case, the analysis indicated no significant impact if recycling was not included, presenting similar values lower than 15% of total impact for both cases.

The basic elements for the construction of the dish-Stirling facility were: engine, dish receiver (glass fiber), metallic structure (construction steel) and concrete for settlement. The concrete supporting the metallic structure has a strong implication in the operation of the dish-Stirling unit due to stability. The concrete guarantees the proper operation of the tracking system that follows the sun rays to provide the adequate shape and position of the concentrated energy.

The description of the SOLO-161 engine (Stirling Systems GmbH, 2007) was utilized. The Stirling engine basically consists of the following subcomponents: heat exchanger, expansion cylinders and pistons, connecting rods, electric generator and regenerator. The materials used in the Stirling engine include different types of steel, copper and nickel alloys. The heat exchanger is also joined to a ceramic cavity for caption of sun rays. In addition to material, the production processes include cold and hot work for metallic materials, joining techniques (welding and brazing) and general product manufacturing technologies. The transport has been included for each material, but not for the entire facility because it was considered that assembly is carried out on site. The disposal was defined for metallic, glass, ceramic and plastic materials. Table 4 presents a summary of materials and manufacturing processes for the components of the dish-Stirling facility.

The photovoltaic system (monocrystalline silicon technology) was characterized using the Ecoinvent database. The inventory of the system included cell construction, photovoltaic panel, electric installation, and AC/DC converter, in addition to a typical installation on a roof. Transport and energy necessary for processes was also included. The corresponding process was used to define a 10 kW facility: 3 kWp photovoltaic facility, façade installation, single-Si, laminated, integrated, at building. The assembly used 3.33 units of the aforementioned 3 kWp facility (which

Table 4

Summary of definition of materials and processes for the dish-Stirling system.

	Material (s)	Quantity (kg)	Process (es)
Concrete settlement	Concrete	150,000	
Metallic structure	Steel	3700	Cold working
Dish receiver	Glass fiber	113.4	
Engine			
<i>Sub-components</i>			
Heat exchanger	Nickel alloy	12	Cold working Casting Electric welding Brazing
Cylinder/piston	Steel	200	Cold working Forging Machining
Connecting rods	Steel	100	Cold working
Electric generator	Steel copper	5050	Cold working Casting
Regenerator	Steel	30	Cold working
Ceramic cavity	Ceramics	15	

included inverter, electric installation, roof installation, photovoltaic panel single-Si, and transport).

4.4. Life Cycle Assessment results

The LCA results were the (i) inventory results; and (ii) impact evaluation results. The calculation conditions considered for these results were: 10 kW functional units of dish-Stirling and photovoltaic facilities with a lifetime of 30 years, taking into account the construction of the facility but not the operation phase (considered negligible). Recycling of materials was considered for both facilities.

4.4.1. Life Cycle Inventory (LCI)

The inventory results were calculated through the addition of effects (emissions and resources) caused by all materials and processes involved in the definition of the facility. These effects represent the environmental outputs, corresponding to different categories, such as gaseous, liquid or solid emissions. The values obtained depend on the database used in the characterization of material and processes. Four gaseous emissions were considered in this work: CO₂, SO_x, NO_x and volatile organic compounds different from methane (NMVOC). CO₂ emissions were a major concern due to its contribution towards the greenhouse effect, being frequently used as a basis for environmental evaluation. CO₂ emissions will therefore be used in comparisons with other studies that analyse dish-Stirling and photovoltaic facilities. The CO₂ emissions are presented as emissions of CO₂ plus CO₂-equivalent, accounting also for the equivalent effect of methane, nitrous oxide, hydrofluorocarbon gases, perfluorocarbon gases and sulfur hexafluoride. The CO₂-equivalent emissions have been calculated by means of the impact evaluation method IPCC 2007 (GWP 100 years). IPCC values have been compared against the IMPACT 2002 + method, in order to ensure similar values. This was confirmed with calculations by using SimaPro.

Remaining gaseous emissions were selected due to their implication in different environmental effects. SO_x emissions are responsible for acid rain, a complex chemical phenomenon that takes place when sulfur and nitrogen compound emissions react with other substances in the atmosphere. These pollutants are carried far from their sources by wind. Depending on the weather, the acid pollutants fall to Earth in wet form (acid rain, snow, mist or fog) or in dry form (acid gases or dusts) (EPA, 2011). NO_x are the main component of photochemical smog, related to ozone layer degradation, also responsible for acid rain. NMVOC are compounds formed mainly by hydrocarbons and some chemical groups, such as alcohol, aldehydes, alkanes, aromatics, cetones and halogen derivatives. NMVOC can be extremely dangerous for human health depending on the composition and toxicity, and when mixed with other atmospheric pollutants, such as NO_x, NMVOC react and form ozone at ground level, which is toxic for human health, contributing to

photochemical smog. The inventory results for the dish-Stirling and Photovoltaic facilities are presented in Table 5.

The gaseous emissions are represented in terms of emissions per kWh produced per facility, taking into account the lifetime of 30 years for each facility.

From Table 5 it can be observed that the order of magnitude of the emissions is the same for both facilities. The CO₂-equivalent emission values are more favorable for the photovoltaic facility, although the difference is not quite significant, especially if considering the uncertainties embedded in the definition of the systems. Modifications in such definitions could alter this favorable balance. As for the rest of emissions, values are generally more favorable for the dish-Stirling facility but also without a significant difference.

Literature results also show values within the same order of magnitude (Stopatto, 2008), but with a greater difference for the dish-Stirling facility. For the photovoltaic facility, the current value for monocrystalline photovoltaic technology presented in Fthenakis and Kim (2011) is 37 g-CO₂-eq/kWh, with a foreseen evolution to future values around 10 g-CO₂-eq/kWh, which is in good accordance with the value of 24.88 g-CO₂-eq/kWh obtained herein.

Cavallaro and Ciraolo (2006) present a value of 7.3 g-CO₂-eq/kWh for the dish-Stirling facility, showing a clear difference from the value obtained in this study: 37.66 g-CO₂-eq/kWh. It must be pointed out that, apart from the differences in the tools utilized, the definition of the system is significantly different, especially in size: 1 MW with 17 solar dishes and five Stirling engines driven by steam vs. 10 kW with one solar dish driving one Stirling engine (large scale application is compared with a facility for distributed generation).

Evaluation of embodied energy for the construction of both facilities can also be obtained from inventory results. The dish-Stirling facility presents a value of 59 GJ vs. 125 GJ for the photovoltaic facility. These values were calculated by adding the energy (originated from different sources) required for the production of the different components of the facilities. No data was found on the dish-Stirling technology so no comparison can be made. In the present study, the surface for the photovoltaic facility is 73.2 m² so a value of 1708 MJ/m² was obtained. For the dish Stirling facility, a value of 1040 MJ/m² was obtained (56.7 m² facility area), which is significantly lower than for the photovoltaic facility. The energy payback period for the dish Stirling is approximately 0.6 years vs. 1.3 years for the photovoltaic facility, considering the same operation time per year for both 10 kW facilities.

A standard reference operation time of 8 h was considered, considering the entire year as useful time, and then corrected by a use factor of 0.9 resulting in a value of 94,600 MJ/year. It has also been considered that energy production for both systems is the same, although there are differences in energy conversion efficiency, which

Table 5
Results of Life Cycle Inventory.

System	Stirling	Photovoltaic
Carbon dioxide (g CO ₂ /kWh)	36.85	22.34
Carbon dioxide-equivalent* (g CO ₂ -eq/kWh)	37.66	24.88
Sulfur oxides (g SO _x /kWh)	0.047	0.073
Nitrogen oxides (g NO _x /kWh)	0.050	0.048
Volatile organic compounds different from methane (g NMVOC/kWh)	0.012	0.025

* (Method IPCC 2007 GWP 100a); similar to method IMPACT 2002+ results.

ultimately favor dish Stirling technology (in principle, dish-Stirling technology should have an energy conversion efficiency almost double of that of photovoltaic, and therefore the estimated emissions for the dish-Stirling are probably higher than what they should be). Nevertheless, this assumption has been made because dish Stirling technology is still currently under development; moreover, the conclusions obtained would not change with a more precise efficiency estimate because the scope of this study is to obtain an order of magnitude of the environmental burden

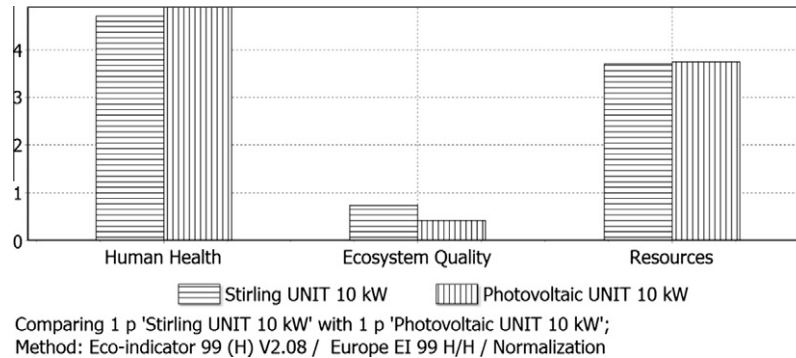


Fig. 3. Normalised damage categories Eco-indicator 99 H/H for comparison of Stirling and photovoltaic units.

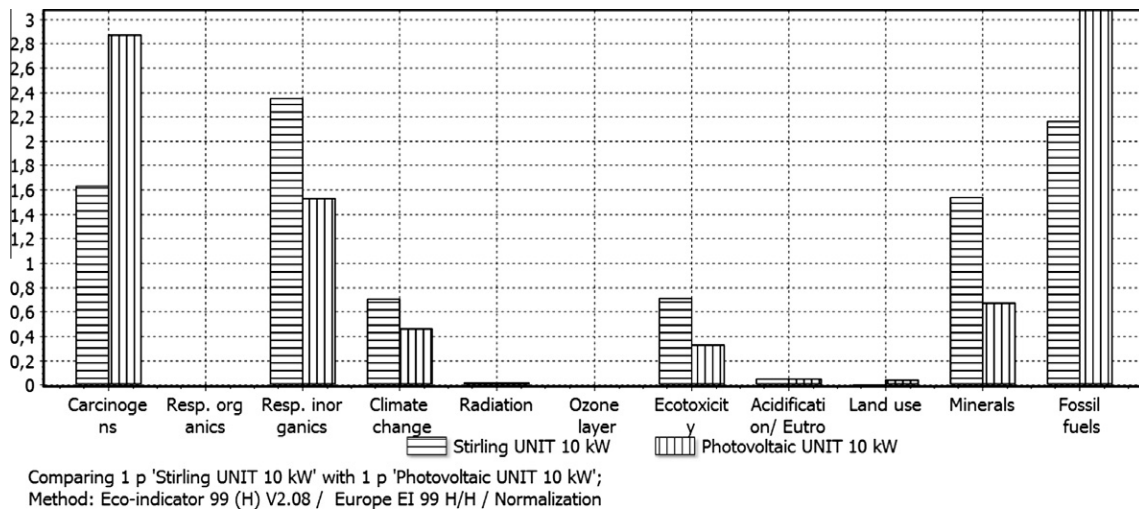


Fig. 4. Normalised impact categories Eco-indicator 99 H/H for comparison of Stirling and photovoltaic units.

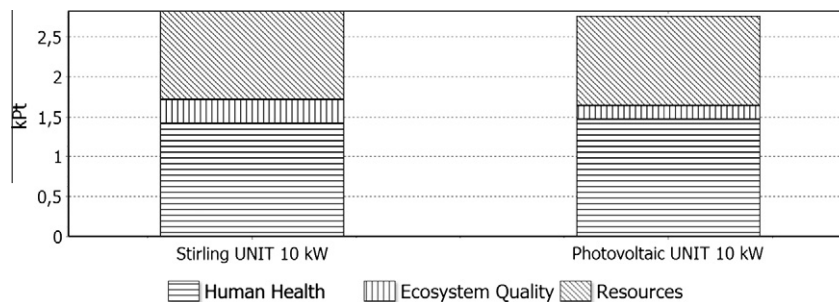


Fig. 5. Single score Eco-indicator 99 H/H for comparison of Stirling and photovoltaic unit.

associated with this new technology. The packing factor should be considered in the case that these technologies were used in generation plants where a number of units of each technology are installed to provide a specific design power. The packing factor has not been considered in this study because the 10 kW facilities are intended to be used in a distributed energy facility, where no interaction between elements has been considered. Therefore, for the dish-Stirling technology only one paraboloidal dish has been considered, and for the photovoltaic, cells located on a roof were considered.

4.4.2. Impact evaluation results

Damage models are used to convert the inventory results into impact category results. The EI-99 impact evaluation method further converts these impact categories into damage categories. Translation of environmental loads into damage categories helps understand and interpret results. In the case study, the impact evaluation results are presented in the three EI-99 damage categories: human health, ecosystem quality and resources. EI-99 enables the aggregation of the three categories into a single score, which was used here basically to simplify

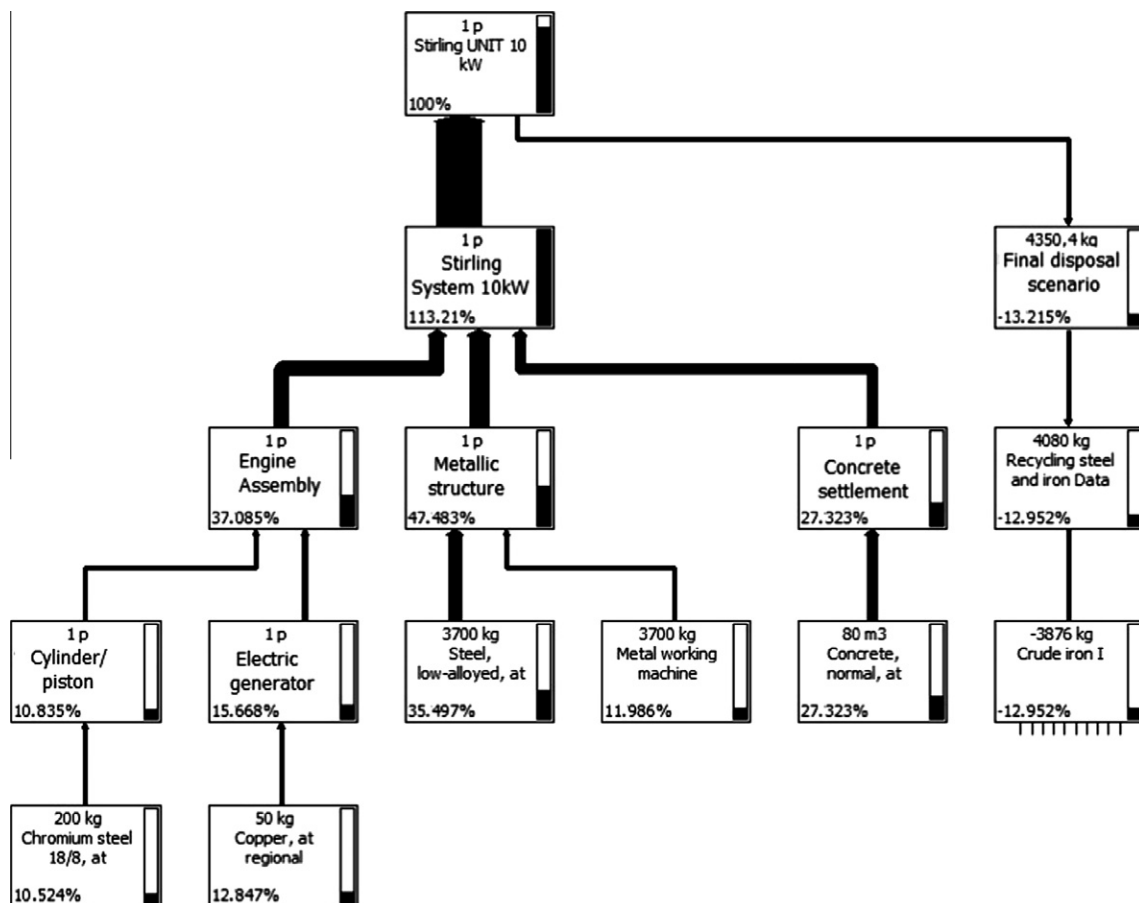


Fig. 6. Contribution tree Eco-indicator 99 H/H of Stirling unit.

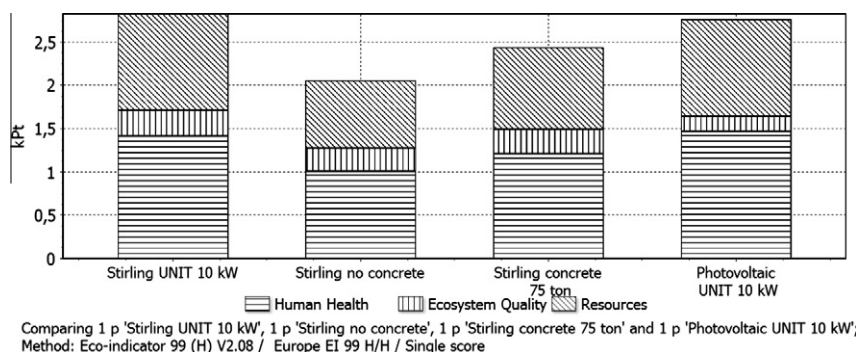


Fig. 7. Sensitivity analysis for concrete contribution/single score. Method Eco-indicator 99 H/H.

comparisons between systems. Additionally, the environmental loads were also evaluated by the CML2 method to verify the validity of results.

The impact evaluation focuses on the comparison of the damage evaluation of a 10 kW dish-Stirling facility vs. a 10 kW photovoltaic system. The impact evaluation methods used were EI-99 (Hierarchist perspective, H/H) and the CML2 method.

The comparison between the dish-Stirling and photovoltaic system is presented for the three damage categories (human health, ecosystem quality and resources) and single score. For both systems it is considered that most materials are recycled at disposal. Fig. 3 shows the environmental evaluation in relation to the three damage categories.

The values shown in Fig. 3 indicate that the level of damage is similar for both systems considered. Ranking the damage categories (from highest to lowest damage): resources, human health and ecosystem quality. The final result for EI-99 H/H are damage categories, but the mid-point evaluation of impact categories can be also obtained, as depicted in Fig. 4.

Analysis of Fig. 4 shows favorable balances for dish-Stirling vs. photovoltaic in different categories. Presentation of the single score enables a direct comparison between the systems, as presented in Fig. 5, where a favorable balance towards the photovoltaic system is shown, but without significant differences in values.

Regarding the dish-Stirling unit, the most significant result is the contribution analysis, where the elements and processes that represent a highest environmental impact are stressed. The contribution analysis is presented in Fig. 6 as the contribution tree (contribution expressed in percentage), with also a graphic showing the contribution (EI-99 points) towards the single score.

The metallic structure presents the highest impact (47.48%) followed by the engine (37.09%), and concrete base (27.32%). The weight of the impact is mainly due to

the contribution of the materials used, such as steel in the metallic structure, instead of the processes considered. The contribution analysis enables the considerations of modifications or future developments to reduce the environmental impact, carried out through a sensitivity analysis, where the characteristics of the systems are modified in order to verify the evolution of the environmental impact.

In the case of the dish-Stirling facility, a feasible modification would be to alter the amount of concrete used in the base. Although the percentage contribution is not the highest (26% vs. 37% of the engine vs. 47% of the metallic structure), it seems to be the most over-dimensioned element used currently in the facility, according to data provided for the Odiello facility (Guillot, 2009). Logically, the impact of modifying the elements with higher contribution percentage would be interesting, but there is no data available to foresee future evolutions. Fig. 7 shows the impacts dynamics of the dish-Stirling facility, from the current concrete value (150 ton) to 0 ton, with 75 ton as a medium value. Fig. 7 shows that the favorable balance in relation to the photovoltaic system is inverted when the quantity of concrete is reduced.

With more data available on the definition of the dish-Stirling facility and its dynamics, a more complete comparison evaluation could be carried out by means of different sensitivity analysis. This would help to define a more environmentally-optimized dish-Stirling system.

The CML2 evaluation was utilized to verify if conclusions regarding the comparison of dish-Stirling and photovoltaic units are consistent and independent on the impact evaluation method. CML2 evaluation is analysed for the method's the impact categories, presented in Fig. 8.

As in the Eco-indicator 99 method, the evaluation for both technologies shows some differences, but they are not significant. The most important impact categories are fresh water aquatic and marine aquatic ecotoxicity, showing a slight difference for both systems.

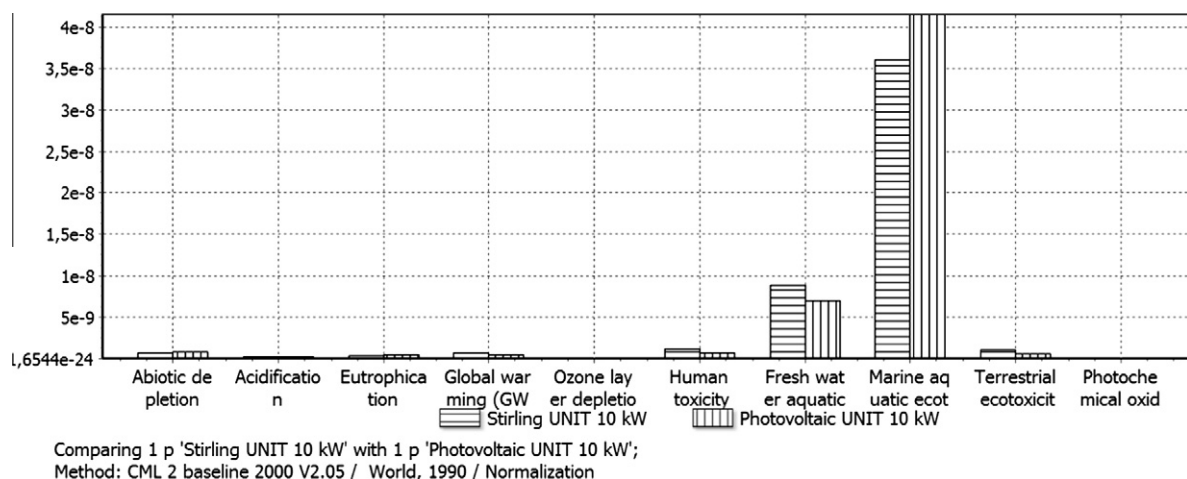


Fig. 8. Normalised impact categories CML2 for comparison of Stirling and photovoltaic units – Normalization.

5. Conclusion

An environmental evaluation of a 10 kW dish-Stirling facility was carried out and compared with a similar photovoltaic facility. The comparison used the environmental outputs of the inventory as well as the environmental impact valued by damage categories. SimaPro software was utilized, with Ecoinvent database and Eco-Indicator 99 and CML2 impact evaluation methods. It was concluded that the comparative results were independent of the impact evaluation method. The main outcomes were:

- The results for CO₂ emissions present the same order of magnitude, with a non-significant balance favorable to the photovoltaic facility.
- The damage categories ranked from highest to lowest damage are: resources, human health and ecosystem quality.
- There were no significant differences between the single scores of dish-Stirling and photovoltaic systems. The analysis showed a difference of approximately 10% in favor of the photovoltaic facility.
- Contribution analysis highlighted the most impact-causing materials: metals (steel for construction), followed by concrete and production processes.
- Sensitivity analysis showed that the dish-Stirling system can be further optimized by decreasing the amount used of: steel for construction (structure) and concrete (base). The decreases can suppose advantages for this technology, which is not yet mature and still at a development stage.

The environmental impact of the dish-Stirling technology was in good accordance with other renewable energy systems. In particular, dish-Stirling technology presented a similar value when compared to a photovoltaic energy system, which is the main competition technology, with similar implementation conditions. Nowadays the dish-Stirling technology is presented as a promising technology but still in a development phase.

Apart from optimizing the current definition of the facility, further improvements could be implemented. In particular, hybridization could be a key issue for this technology. Hybridization is the combination of the solar energy with other sources, to provide a more extended service, thus minimizing environmental impacts and improving the amortization of investments. The advantages could be significant if the additional source is a renewable source, such as biogas. Thermal energy storage could also be included in the dish-Stirling facility, further optimizing its utilization. It is estimated that these two developments, applicable to the dish-Stirling technology (but not to photovoltaic systems) would improve the environmental performance of the dish-stirling. However this estimation should be rigorously evaluated through an appropriate Life Cycle Assessment.

There are also other issues to be taken into account, such as the occupied surface. For the 10 kW facilities considered, the surface is 56.7 m² for dish-Stirling vs. 73.2 m² for photovoltaic facility. Based on the previous assumption that both technologies present similar energy conversion efficiencies, dish-Stirling requires approximately 25% less surface than photovoltaic, which is an advantage.

Future evaluations of the technology should also consider uses in distributed generation or large scale applications, which could be decisive in an environmental evaluation. Thus, the dish-Stirling technology faces different technological challenges. It is necessary to work towards the development of a profitable and reliable system to generate electricity, guaranteeing a continuous operation in combination with other renewable sources to minimize the environmental impact.

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